Potential resonances for oscillatory structure in second energy derivative of fusion cross section times energy

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Using a weakly absorptive potential for the nucleus-nucleus collision, the S-matrix of the reaction is derived and in terms of this the reaction cross section σ_R is expressed as function of incident center of mass energy E_{cm}. The weakly absorptive potential in different angular momentum trajectories is found to generate resonances which are manifested as peaks/maxima in the values of σ_R at specific energies of resonances. In a natural consideration, a part of σ_R is taken as fusion cross section σ_F. Hence, the results of σ_F contain all important resonance character found in the results of σ_R. These results of σ_F when presented in the form $D_F(E_{cm})= \frac{d^2(E_{cm}\sigma_F)}{dE_{cm}^2}$ exhibits oscillatory structure with peaks and deeps in its variation with E_{cm}. We obtain our theoretical results of this quantity $D_F(E_{cm})$ using a new form of potential capable of generating sufficient resonances and account for the corresponding results of $D_F(E_{cm})$ extracted from experimental data of σ_F having positive peaks and deeps including negative deeps in the case of the $^{36}S+^{110}Pd$ system with remarkable success. With this we come to the conclusion that the development of resonances in heavy-ion collision is the doorway to the generation of oscillatory structure in the results of second energy derivative of the fusion cross section times energy.

The proposed potential as a function of radial variable r is given by

$$V_N^R(r) = \begin{cases} -V_0 \frac{4(1-c)r\rho^3}{(r^2-\rho^2)^2}\frac{(1-e^y)e^y}{(1-ce^y)^3}, & \text{if } r < \rho, \\ 0 \quad , & \text{if } r \geq \rho, \end{cases} \tag{1}$$

where $y = \frac{r^2}{r^2-\rho^2}$ The strength $V_0 > 0$ and is in MeV unit. The radius ρ is expressed as $\rho = r_0(A_1^{1/3} + A_2^{1/3})$ in terms of distance parameters r_0 in fm unit, and mass numbers A_1 and A_2 of the partner nuclei. This real nuclear potential $V_N^R(r)$ (1) in combination with the Coulomb potential $V_C(r)$ and centrifugal potential $V_\ell(r)$ generates a repulsive barrier in the outer region with a prominent pocket in the inner side in each partial wave trajectory specified by ℓ=0, 1, 2, 3..... A negative imaginary potential $V_N^I(r) = -W_0 exp(\frac{a_i r^2}{r^2-\rho_i^2})$ is added to the real potentials in the optical model description of nucleus-nucleus collision and scattering.

The Schrödinger equation with the total complex potential $V(r)=V_N^R(r)+V_C(r)+V_\ell(r) - iV_N^I(r)$ is solved by using a convenient method developed by us [1] and analytical expression for the wave function is obtained in the form $\Phi_j(r) = a_j e^{ik_j r} + b_j e^{-ik_j r}$ in a segment j. The contribution to absorption or reaction cross section from the region $0 < r < R_F$ is considered to account for the fusion cross section σ_F at a given energy $E=\frac{\hbar^2}{2m}k^2$. This can be expressed as

$$\sigma_F = \frac{\pi}{k^2}\sum_\ell (2\ell+1)(\sum_{j=1}^{n_F} I_j^{(\ell)}), \tag{2}$$

where I_j^ℓ indicates absorption in the jth segment for a given ℓ. R_F is a radial position within the pocket region. The total number of segments to be considered in the summation of (2) is defined by $n_F = \frac{R_F}{w}$ with w indicating the width of each segment. Using the results of σ_F given by (2) at different energy one can extract the results of fusion distribution function $D_F(E) = d^2(E\sigma_F)/dE^2$

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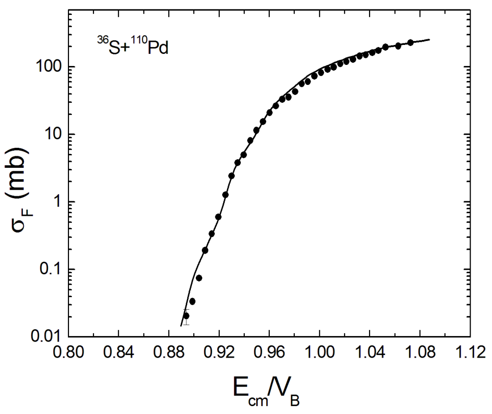

FIG. 1: Variation of fusion cross section σ_F as function of center-of-mass energy E_{cm} divided by barrier energy V_b=89.15 MeV for $^{36}S+^{110}Pd$ system. The solid curve represents the results of present optical model (S-matrix) calculation. The experimental data shown by solid dots are obtained from ref. [2].

by using a three-point-difference formula for the double energy derivative with some value of energy step ΔE. We apply our formulation to the case of $^{36}S+^{110}Pd$ system where the measured results of $D_F(E_{cm})$ show highly oscillatory structure even in the s-wave barrier energy region. The values of the potential parameters are V_0=28.3 MeV, r_0=1.61 fm, c=0.77, r_C=1.2 fm, W_0=.5 MeV, r_{0i}=1.6 fm, a_i=0.04 and the fusion radius R_F =9.1 fm. We plot our results of σ_F by solid curves in fig. 1 and the reduced quantity of D_F(E) equal to $(1/(\pi R_b^2)d^2(E_{cm}\sigma_F)/dE_{cm}^2$ with barrier radius R_b=11.10 fm in fig. 2 as a function of E_{cm} in MeV divided by barrier height V_b=89.15 MeV and compare them with the corresponding experimental data shown by solid dots [2]. It is seen that our calculated results (solid curve) of σ_F in fig. 1 explain the corresponding measured data (solid dots) quite well over a wide range of energy that includes both sub-barrier and above barrier regions. The reduced results of $D_F(E_{cm})$ calculated using energy step size ΔE_{cm}=0.8 MeV are shown by a solid

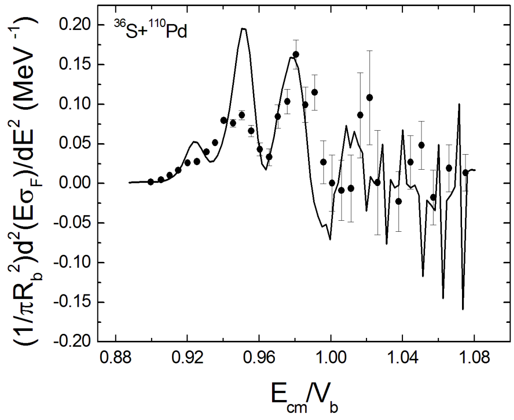

FIG. 2: Variation of experimentally extracted results (solid dots) [2] of the quantity $D_F(E) = d^2(E\sigma_F)/dE^2$ divided by πR_b^2 with barrier radius R_b=11.10 fm as a function E=E_{cm} divided by V_b=89.15 MeV corresponding to results of σ_F in Fig. 1. The solid curve represent the results of present calculation obtained by using energy step ΔE= 0.8 MeV.

curve in fig. 2. It is clearly seen that the oscillatory structure in the measured data (solid dots) [2] with few broad peaks in the barrier region of energy and large number of positive peaks and negative deeps in the high energy region is accounted for by our calculated results shown by a solid curve with remarkable success.

References

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